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Investigation the effect of Air-Blast Explosion on reinforced concrete Structures: Case Study of Yemen

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ABSTRACT
Aden, the economic capital of Yemen, has experienced several civil wars that resulted in significant damage to its infrastructure and numerous private and public buildings. This study focuses on Some buildings in Aden city as case studies to evaluate the effects of explosions on these buildings. The goal is to assess the impact on buildings directly or indirectly exposed to bombings. Field visits were conducted to investigate the damage to a sample of neighboring buildings, including those directly targeted. The purpose is to find solutions to mitigate such damages and prevent them in the event of future targeting of any building. This study also introduces the analysis of these buildings which damaged by three explosions. Buildings 1, 2, and 5 were directly targeted and hit by guided missiles containing a payload of 250 kg per shell while buildings 3, 4, 6, 7, 8, and 9 were indirectly exposed by these explosions. Findings revealed that damage was influenced by the distance from the explosion center, building age, and construction materials used. These factors provided valuable insights for damage assessment and treatment. The study concluded that it is crucial to release the compressed gas generated by the explosion through hatches in enclosed areas of buildings. If these hatches affect the functioning of these areas, weak points should be incorporated into the walls to act as paths for the blast wave, allowing it to dissipate more effectively and minimize damage to the concrete structure.
Keywords: *Explosion; Peak pressure; Air blast; Shock wave; Reflected shock*

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I. INTRODUCTION

In recent years, regional wars and terror activities have caused blast-loading effects on reinforced concrete buildings, resulting in catastrophic human and material damage. When a building is exposed to a blast load, a very high air pressure affects the building within a very short duration [1].

During war and terrorist activities, some concrete buildings are exposed to a direct or indirect shelling. The effect of these bombs on buildings differs in terms of the size of the target and the distance between the building and the center of the blast [2, 3]. This paper aims to examine the effects of an explosion on a building that is directly exposed to an air shell through field investigations. Additionally, it also intends to explore the impact of the explosion on nearby buildings.

Concrete has been a widely utilized construction material for many years and continues to be prevalent in various types of construction projects, ranging from small local structures to towering skyscrapers. In modern construction practices, façade systems are recognized as integral components of building design and construction[4].

The widespread use of destructive weapons by armies and terrorists has highlighted the vulnerability of concrete structures to explosions, whether they are directly or indirectly affected. To assess the impact of an explosion on concrete buildings and the surrounding area, several important factors need to be considered [5-8]:

- Building Location and Confrontation: The position of the building in relation to the explosion center plays a significant role. Buildings closer to the center are more likely to experience severe damage compared to those farther away.
- Distance from the Explosion Center: The distance between the building and the explosion's center affects the intensity of the impact. Buildings in closer proximity to the center are subject to greater forces and higher levels of destruction.
- Building Height: The height of a building can influence its response to an explosion. Tall structures may experience amplified effects due to the propagation of shockwaves or the potential for collapse under the influence of blast forces.
- Level of Construction: The level of construction relative to the explosion center is crucial. Buildings located at higher elevations may be exposed to more intense forces and damage, especially if they are directly facing the blast.
- Building Age: The age of a building can affect its ability to withstand an explosion. Older structures may have weaker materials, outdated construction methods, or inadequate structural reinforcement, making them more susceptible to damage.
- Building Materials: The materials used in constructing the buildings also play a vital role. Different materials have varying resistance to explosions. Concrete, for example, may exhibit different behaviors depending on its composition, reinforcement, and quality.

These factors are crucial for understanding the impact of explosions on concrete buildings and their surroundings. By assessing these variables, experts can develop strategies to enhance the resilience of structures and mitigate the potential damage caused by explosions.

Numerous concrete buildings in the city of Aden have been subjected to direct or indirect shelling, resulting in varying degrees of damage. The extent of the damage depends on factors such as the size of the target, the distance from the blast center, and the type of shells used in the attacks. These events have had a significant impact on the structural integrity and condition of the affected buildings in Aden [9]. The objective of this paper is to examine the impact of direct explosions on buildings, as well as the subsequent effects on neighboring structures. The study aims to analyze the consequences of explosions on targeted buildings and evaluate the potential collateral damage to nearby buildings caused by the blast.

II. EXPLOSION

An explosion is defined as the rapid release of energy within a short duration, typically less than one-thousandth of a second. It involves the generation of high temperatures and the immediate release of a large amount of gas, resulting in the formation of a high-pressure shockwave with a predetermined maximum intensity [10, 11].

Detonation refers to a fast and stable reaction that takes place within explosives, with a speed of approximately 7620 m/s. This reaction rapidly converts solid or liquid explosives into a dense, high-pressure gas. As a result, powerful blast waves are generated, causing significant impact and damage in the surrounding area [12].

III. EXPLOSION LOADING CATEGORIES

Explosion loadings can be categorized into two main groups based on the level of confinement of the explosive load. These groups are confined and unconfined explosions. Figure 1 provides an overview of the different categories of loading that can occur in relation to these types of explosions [13].

3.1 Confined explosions

The initial wave fronts generated by an explosion occurring inside a structure can create very high peak pressures. The extent of pressure and duration of load within the structure depend on factors such as the level of confinement, elevated temperatures, and the buildup of gaseous byproducts resulting from chemical reactions during the blast. Inadequate structural resistance against internal stresses can lead to a failure of the structure due to the combined impact of these stresses. Effective ventilation systems can reduce the strength and duration of pressure, resulting in significant variations in the pressure effects between structures equipped with ventilation hatches and those lacking them [9, 14].

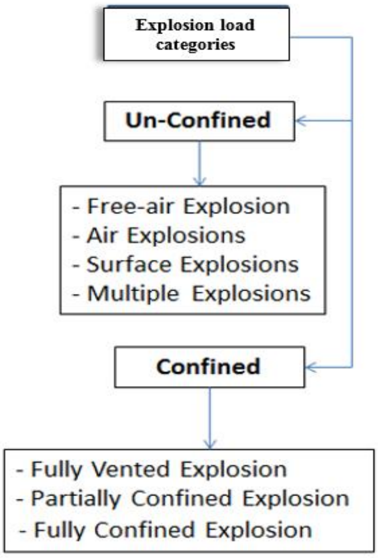

Figure 1: Explosion load categories[9]

3.2 UNCONFINED EXPLOSIONS

An open-air explosion generates a wave that directly propagates from the explosive source to the structure, bypassing typical wave propagation. These explosions are strategically positioned at a specific distance and height, intentionally kept away from the structure. [13, 15].The effect of explosions has a greater impact on multi-story buildings compared to single-story structures. The explosions cause more significant damage or swelling on buildings with multiple levels as shown inFigure 1.

IV. EXPLOSION LOADS

a-SHOCK WAVE

During an explosion, a rapid and intense pressure wave called a shock wave is generated. This shock wave travels at a speed faster than the speed of sound, extending from the source of the explosion to the surrounding area. As a result, the normal ambient pressure is transformed into a significantly higher pressure known as overpressure. This increase occurs almost instantaneously, within a fraction of a second (around one millisecond), and the highest pressure reached during this process is called the peak overpressure [16, 17].The shock wave generated by an explosion comprises two distinct phases. The first phase is the positive phase, during which the pressure exceeds the normal air pressure by a significant margin. Following this phase, the air permeates, causing the pressure to drop below the ambient air pressure. This subsequent phase is referred to as the negative phase of the wave. The wave undergoes multiple repetitions, each with reduced pressure, until it eventually dissipates completely, reaching a point where the higher pressures of these waves match the atmospheric pressure. This pattern is illustrated in Figure 2.

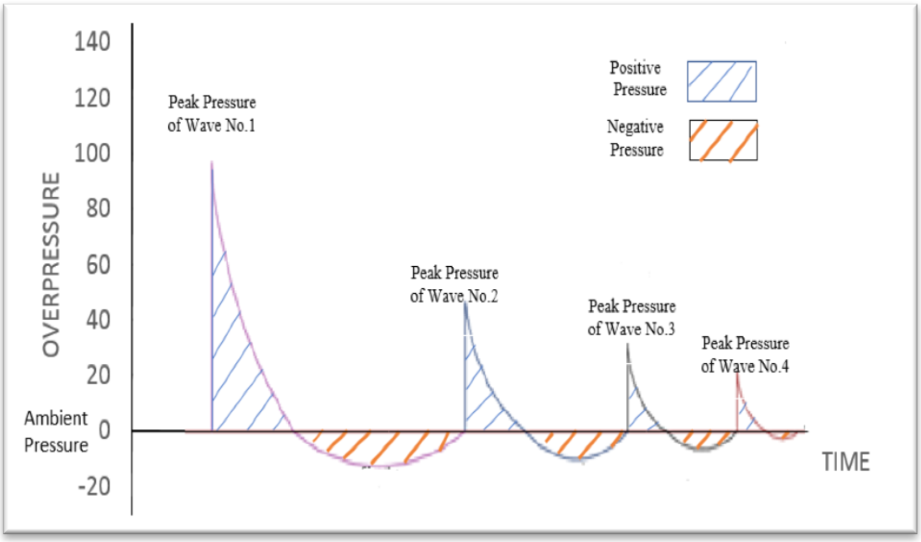

Figure 2: Explosive waves sequence[13, 17]

Figure 3 serves as a reference for determining the ideal attributes of a blast wave. It helps in identifying and establishing the most effective characteristics required for the optimal impact of the blast wave.In order to acquire the precise parameter values for the blast wave, referring to the chart illustrated in Figure 10 is essential. The chart provides the necessary information and data required to determine the specific parameters associated with the blast wave. By utilizing this chart, various parameters thatcontribute to the desired characteristics of the blast wave depicted in Figure 3 can be identified.

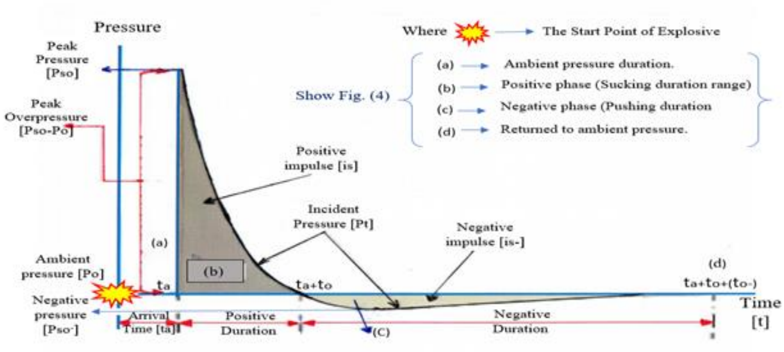

Figure 3: Ideal blast waves pressure time history[18]

*** → t_o = (Start point of ta – end point of ta) for each case**

Where:

P_o: The ambient pressure before explosion.

P_{so}: A positive peak overpressure after explosion at arrival time ta.

t_a: The arrival time which need to convert the ambient pressure to a peak pressure.

t_o:Duration of positive pressure, from peak point to ambient pressure which turns into negative duration.

t_a+t_o: Positive phase duration, Pso comeback to ambient pressure at this duration.

P_o-: The ambient pressure after Pso coming back to its initial ambient pressure at positive phase duration at arrival time ta+to

P_{so}-: A negative peak overpressure.

t_a+ t_o+ (t_o-): Negative phase duration, Pso comeback to ambient pressure at this negative phase duration.

t_o-: Negative phase duration which is longer than positive phase duration.

As the distance from the detonation center increases, two key characteristics of the blast wave, namely the peak overpressure and the speed of the shock wave, decrease. The peak overpressure refers to the maximum pressure reached during the explosion, while the speed of the shock wave denotes the velocity at which the wave propagates through the surrounding area. These values diminish as the distance from the detonation center increases. The negative phase is longer than the positive, its minimum value of pressure is referred to as Pso- and the duration to-. The values of main parameters for each building in case study are shown in Figures 11-19.

b-Reflected Shock wave

When a projectile explodes either in the open air near the ground or inside an enclosed space, it creates a feedback wave upon colliding with the surface of the earth or the walls and floor of the surrounding area. This feedback waves combines with the wave of excess pressure produced by the explosion, resulting in a more powerful pressure wave directed back towards the source of the explosion. This intensified pressure wave is known as the reflected wave[16, 19, 20].

c-Shock Styles Reflected

There are three types of reflection phenomenaduring an explosion:

(1) Natural reflection: This occurs when the shock wave directly hits an unyielding surface, with the plane of the shock wave parallel to the surface,

(2) Oblique reflection: This happens when the shock wave encounters a slight angle between its plane and the reflective surface plane, and

(3) Mach stem formation: This is a spurt-like effect that occurs when the shock wave impacts a surface similar to grazing incidence, resulting in the formation of a Mach stem.[19, 21]

d- Clarification blast wave effect

During an explosion, structures are exposed to suction forcesthat can cause glass fragments from facade failures to be propelled outside the building rather than remaining insideas shown in Figure 4.

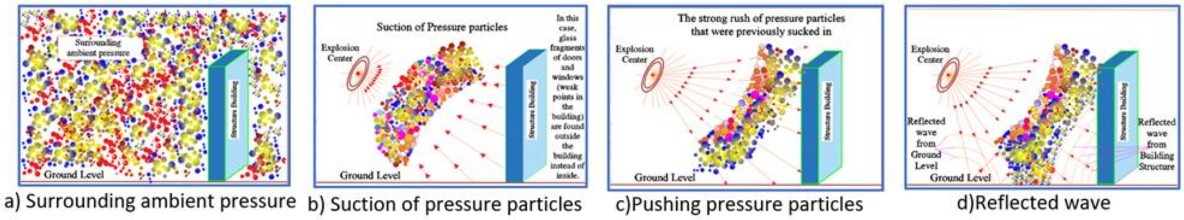

Figure 4: Shock Waves steps sequence

V. CASE STUDY DEMONSTRATION

This research examined numerous case studies involving explosions and found consistent results regarding their effects. The study concluded that several factors, including the height, weight, and ventilation access of a building, along with its distance from the center point of the explosion, determine the extent of damage inflicted on each building. This research shows a unit of nine buildings to be its formal case study and investigated the effect in depth.

The study focused on specific case studies in Aden city, Yemen. It involved nine buildings as shown in Figure 5. Among these buildings, three of which were three were deliberately attacked by guided missiles carrying a 250 kg payload of high explosives (HE).The information regarding the missile strikes and their payload was verified by Project Masam/Supporting entity, an organization specialized in activities such as mine clearance, dealing with improvised explosive devices (IEDs), unexploded ordnance (UXOs), and explosive ordnance disposal (EODs).[23]

The distances between the center of the explosion and the nearby nine reinforced concrete buildings are measured. These distances were visually represented in Figures 6 to 8.

Buil. → Structure Building symbol.

→ Symbol on building's which exposed to direct hit

Figure 5: Studied unit buildings locations, by Google Earth

CASE STUDY NO. (1):
In case study No. (1), building 1 was directly struck by the explosion. Figure 6 provided information about the distances in meters (m) between the explosion's center (building 1) and the nearby buildings.

CASE STUDY NO. (2):
In case study No. (2), building 2 was directly struck by the explosion. Figure 3.3 provided information about the distances in meters (m) between the explosion's center (building 2) and the nearby buildings.

CASE STUDY NO. (3):
In case study No. (3), building 5 was directly struck by the explosion. Figure 3.4 provided information about the distances in meters (m) between the explosion's center (building 5) and the nearby buildings.

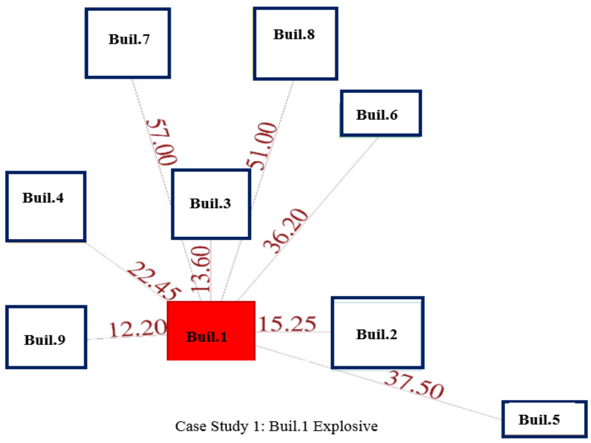

Figure 6: The distances in meters (m) between the explosion's center (Building 1) and the nearby buildings

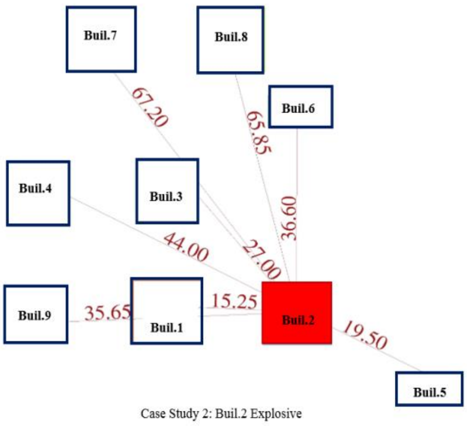

Figure 7: The distances in meters (m) between the explosion's center (Building 2) and the nearby buildings

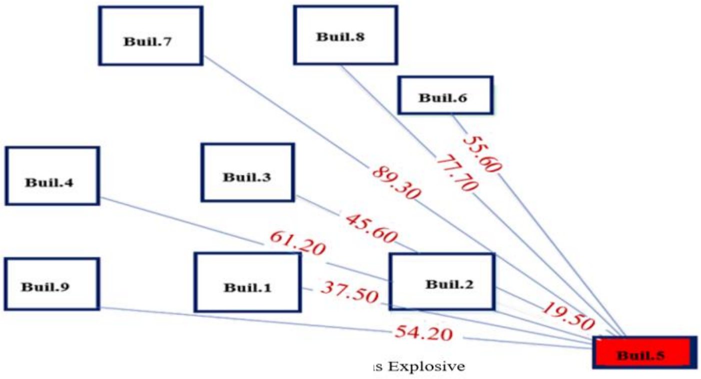

Figure 8: The distances in meters (m) between the explosion's center (Building 5) and the nearby buildings

VI. LAWS TO SCALE

In blast loading calculations, the distance between the detonation point and the neighboring structure is a crucial factor. According to the study, the maximum pressure and speed of the blast wave decrease rapidly with an increase in the distance from the blast source to the neighboring structure as illustrated in Figure 3. The positive phases of the blast waves are shown in Figures (11-19).These phases have a longer duration as the distance from the detonation point increases.The Hopkinson-Cranz law introduces a concept called dimensional scaled distance, which is defined by Equation (1). This law provides a mathematical relationship to analyze the behavior of blast waves. The dimensional scaled distance is a parameter used to scale the effects of explosions based on their distance from the source. Equation (1) describes the specific formula or equation used to calculate this dimensional scaled distance.

$$Z = \frac{R}{[W]^{1/3}} \quad (1)$$

[16, 18 ,24]

where
Z is the scaled distance,
R is the distance from the detonation source to the point of interest [m], and
W is the weight (more precisely: the mass) of the explosive [kg].
Thus, suppose that an explosive charge of weight W1 and situated at distance R1 from the point of interest, produces at this point a blast wave of peak overpressure P, impulse i_1, duration t_{o1}, with arrival time t_{a1} .
Figure 10 provides a reference for determining the scaled distance, which is then used to calculate the positive overpressure peak point for each unit. Table 1 contains the values of the scaled distance corresponding to different parts, while figures 10 to 18 illustrate the specific positive overpressure peak points for each of these parts. These figures allow for the identification and determination of the peak overpressure values associated with different sections or components.

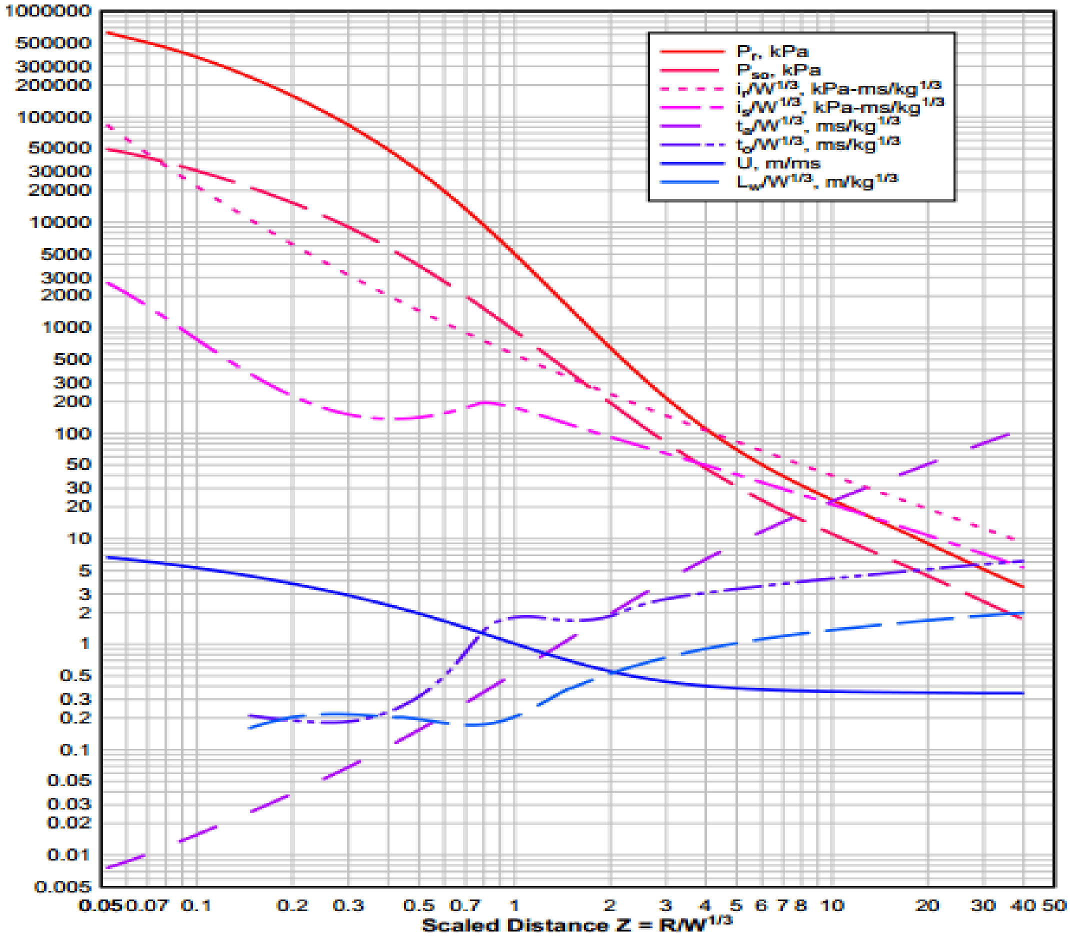

Figure 9: Parameters of positive phase of shock spherical wave of TNT charges from free-air bursts [18, 25]

Table 1:The distance for the intended explosions (Charge weight =250 kg) [23]

Buildings No.	Explosion No.1		Explosion No.2		Explosion No.3	
	Distance (m)	Scaled distance	Distance (m)	Scaled distance	Distance (m)	Scaled distance
Buil.1	0	0.000	15.25	2.421	37.5	5.953
Buil.2	15.25	2.421	0	0.000	19.5	3.095
Buil.3	13.6	2.159	27	4.286	45.6	7.239
Buil.4	22.45	3.564	44	6.985	61.2	9.715
Buil.5	37.5	5.953	19.5	3.095	0	0.000
Buil.6	36.2	5.746	36.6	5.810	55.6	8.826
Buil.7	57	9.048	67.2	10.667	89.3	14.175
Buil.8	51	8.096	65.85	10.453	77.7	12.334
Buil.9	12.2	1.937	35.65	5.659	54.2	8.604

* Distance point to the space in meter between the buildings and the center of explosion.
*0 means the center point of explosion.

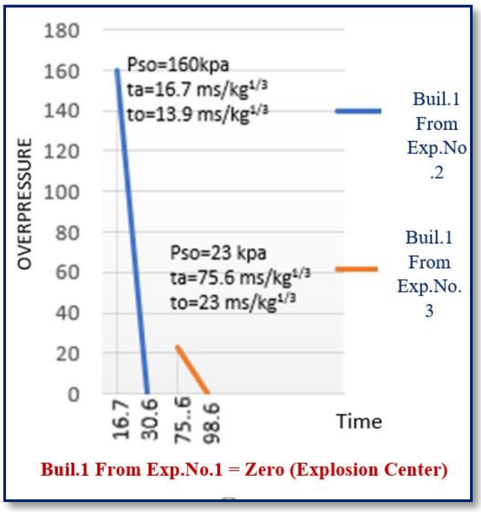

Figure 10: Peak pressure on (Building 1)

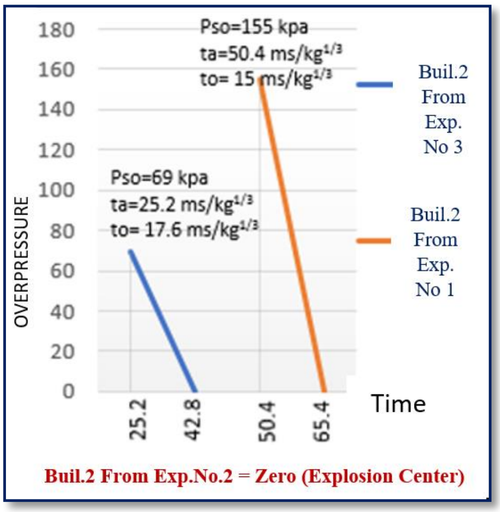

Figure 11:Peak pressure on (Building 2)

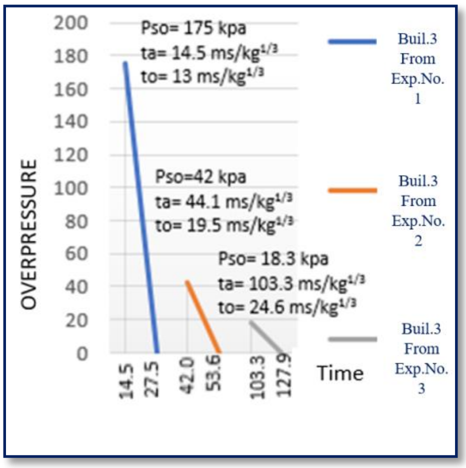

Figure 12:Peak pressure on (Building 3)

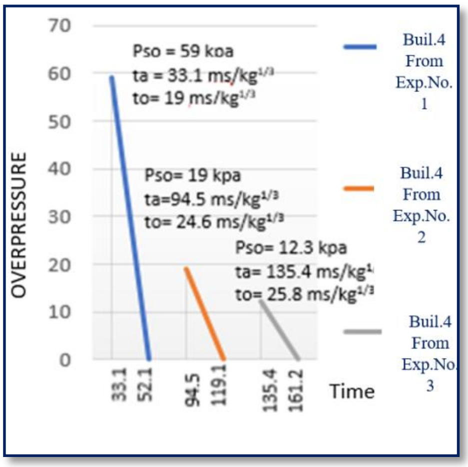

Figure 13:Peak pressure on (Building 4)

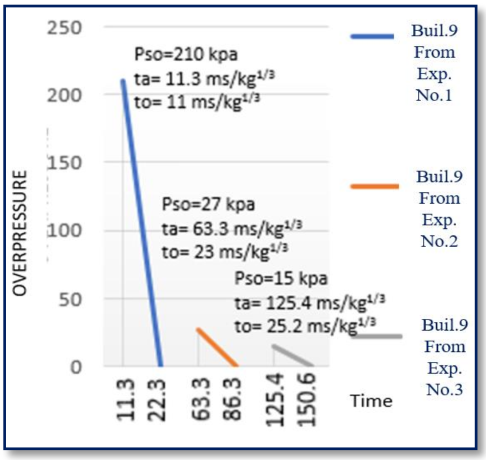

Figure 14: The Peak pressure on (Building 9)

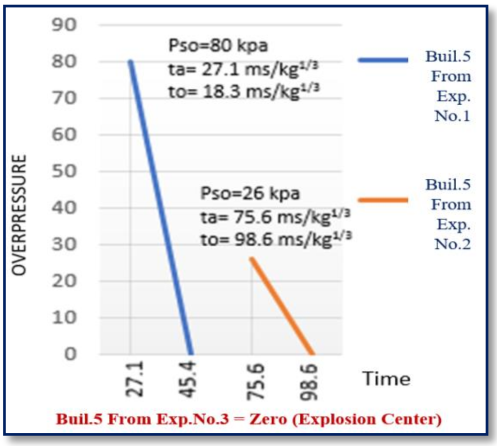

Figure 15: The Peak pressure on (Building 5)

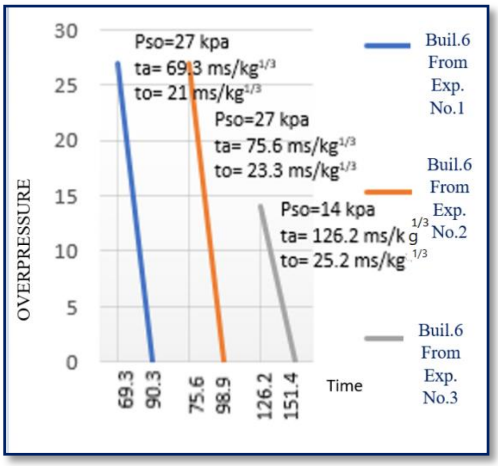

Figure 16: Peak pressure on (Building 6)

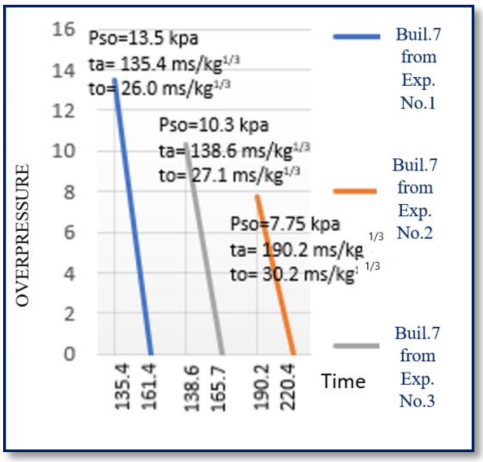

Figure 17: Peak pressure on (Building 7)

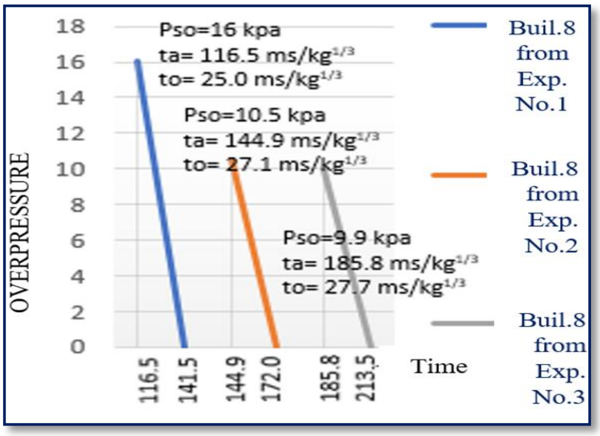

Figure 18: Peak pressure on (Building 8)

Figures 10-18: Explosion Waves on Several Buildings of Case Stady Part (1,2 &3)
* → to = (Start point of ta – end point of ta) for each case

VII. INVESTIGATIONS REPORT

7.1 BEFORE EXPLOSION

• Table 2 presents comprehensive information about the unit of buildings that were studied. This table provides detailed data and specifications related to the buildings under investigation. It likely includes various parameters such as building's foundations, No. of floors, the building condition before explosion, and inclinations (in degree) at 1 m height from ground level.

• Figure 20 Shows Details of studied unit of buildings Locations.

- Buildings 1,2,3,4, and 9 are fully built.
- Building 5 has one story of reinforced concrete structure and it is fully built
- Building 6 has one storyits walls made by bricks and slab made by wood covered with concrete and it was fully built.

•Building 7 is an unfinished building that lacks doors and windows. It consists of five stories.

• Building No. 8 is a three-story structure with a unique construction approach. The foundation footings were implemented without excavation, meaning that they were built above the ground level by compacting the existing soil. The ground and first floors are unfinished, lacking doors and windows. However, the second floor is fully constructed and complete with doors and windows. This building follows a distinct design and construction method, incorporating the necessary soil compaction for foundation.

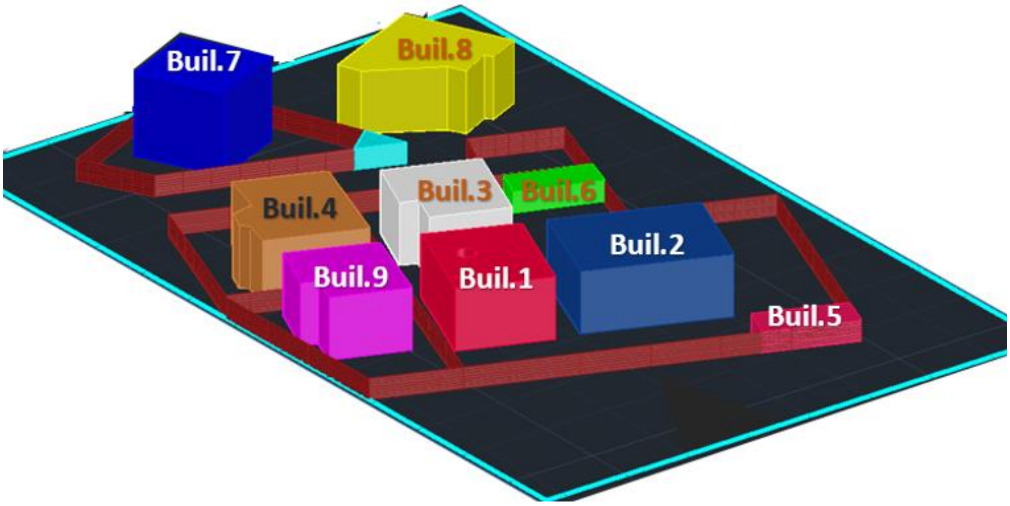

Figure 19: Details of the studied unit building'slocations (Source: Researchers)

Table 2: Information's of unit buildings

Symbols Information	Buil.1	Buil.2	Buil.3	Buil.4	Buil.5	Buil.6	Buil.7	Buil.8	Buil.9
Building's foundations	Under Ground level	Under Ground level	Under Ground level	Under Ground level	Under Ground level	Under Ground level	Under Ground level	Upper Ground level	Under Ground level
No. of Floors (Flats)	3	3	3	3	1	1	5	3	3
The building condition before explosion	Complet ely ready	Complet ely ready	Complete ly ready	Complete ly ready	Complete ly ready	Complete ly ready	Without doors and Windows	Only the third floor is ready	Completel y ready
Inclinations (in degree) At 1 m height from ground level	0.00 Because this building exposed to direct air shell	1 – 3 For the remainde r part of the building	1 - 3	1 - 3	1 - 3	0.00 Because this building exposed to direct air shell	1-3	1 - 3	1 - 3
The distance from each building to the building exposed to the direct explosion is shown in Figures No. (6, 7, 8).									

7.2 POST-EXPLOSION (DESCRIPTION AND ANALYSIS)

The monitoring of the explosion effects reveals the following:

a- Explosions took place in three different locations that were in close proximity to each other, but on different days[23].

b- Table 2 shows information about the subjected buildings.

c- Buildings 1, 2, and 5 were directly targeted and hit by guided missiles containing a payload of 250 kg per shell [23].

The effect on buildings that were directly exposed to the bombing, are as follows:

•**Building 1**:directly exposed to bombing

The investigation analysis indicates that the roofs of the third and second floors collapsed onto the slab of the ground floor. The walls of the ground floor completely collapsed, and there was a total collapse of the stairs. These findings are illustrated in figures 24, 25, 26, and 27.

•**Building 2:**directly exposed to bombing

Investigation Analysis: Almost half of the building completely collapsed due to a direct hitas shown inFigures24 and 25[23].

•**Building 5:** directly exposed to bombing

Investigation Analysis: The building completely collapsed due to a direct hit as shown inFigure 27[23].

d- **Buildings 3, 4, 9 and 6:**that were not directly hit.

Investigation Analysis: these buildings did not suffer significant damage, despite their proximity to the buildings exposed to direct shelling.During the investigation, it was noted that some cracks were observed in the concrete components and certain walls. In addition, it was observed that all doors and windows of the surrounding buildings near the center of the explosion were destroyed. This pattern was consistent across all units that were investigated. The destructive impact of the explosion resulted in the complete destruction of doors and windows in the vicinity of the blast as shown in Figures 25, 26, and 27.

e-Building 8:precisely at the staircase, cracks were observed on the roof of it as shown in Figure 28.

Investigation Analysis: It is worth noting that in the absence of ventilation hatches in the area, the impact of the explosion was relatively limited. The explosion caused cracks in the staircase slab, but this damage was relatively minor as the staircase was located at a considerable distance from the center of the explosion.

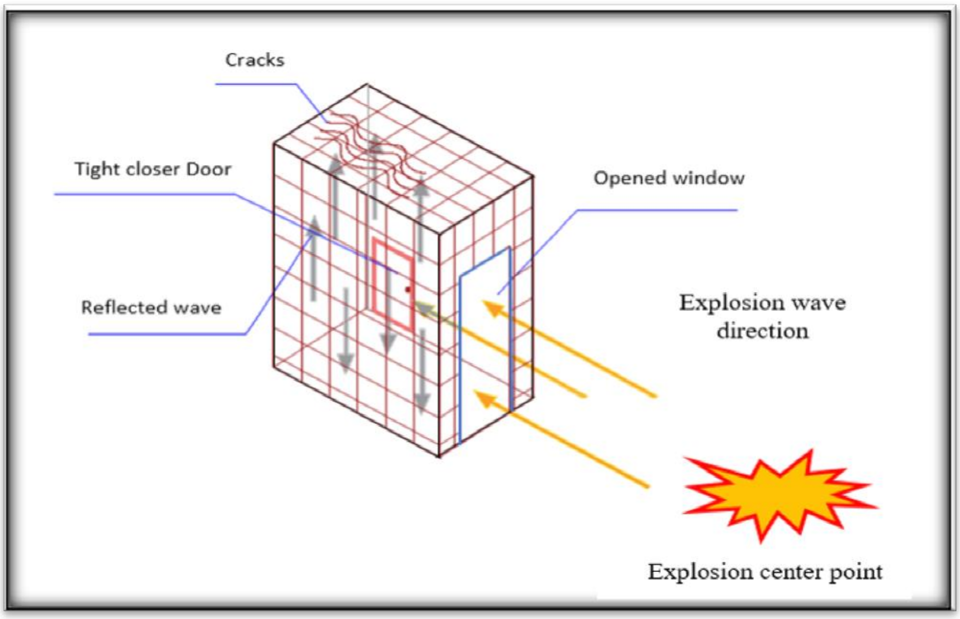

Figure 20: Shows what happened for the wave which entered the part of staircase

f- Building 7: there is no damage

During the investigation analysis, it was discovered that the concrete structure under study did not sustain any damage from the shock wave. This was attributed to the absence of doors and windows, which allowed the blast wave to find an outlet to escape. As a result, the concrete structure remained unaffected. This observation is illustrated in Figure 28.

VIII. DISCUSSION

Based on a case study of a unit of buildings affected by the indirect impact of an explosion, the study draws the following conclusions:

1. The effect of an explosion is significantly greater on buildings without ventilation hatches compared to those with an outlet for ventilation along the same path as the shock wave. The presence of a ventilation out-gate allows the explosion shock wave to find an escape route, reducing its impact on the structure. In this scenario, the effect of the explosion is minimized in comparison to buildings without ventilation hatches.

To mitigate the destructive effects of explosions, it is recommended that buildings be designed with ventilation hatches. Figure 21 suggests incorporating staircase hatches into the building design, while Figure 22 proposes the inclusion of weak points such as flap ventilation gates. These features provide an outlet for explosion waves, helping to minimize the destructive impact on the structure.

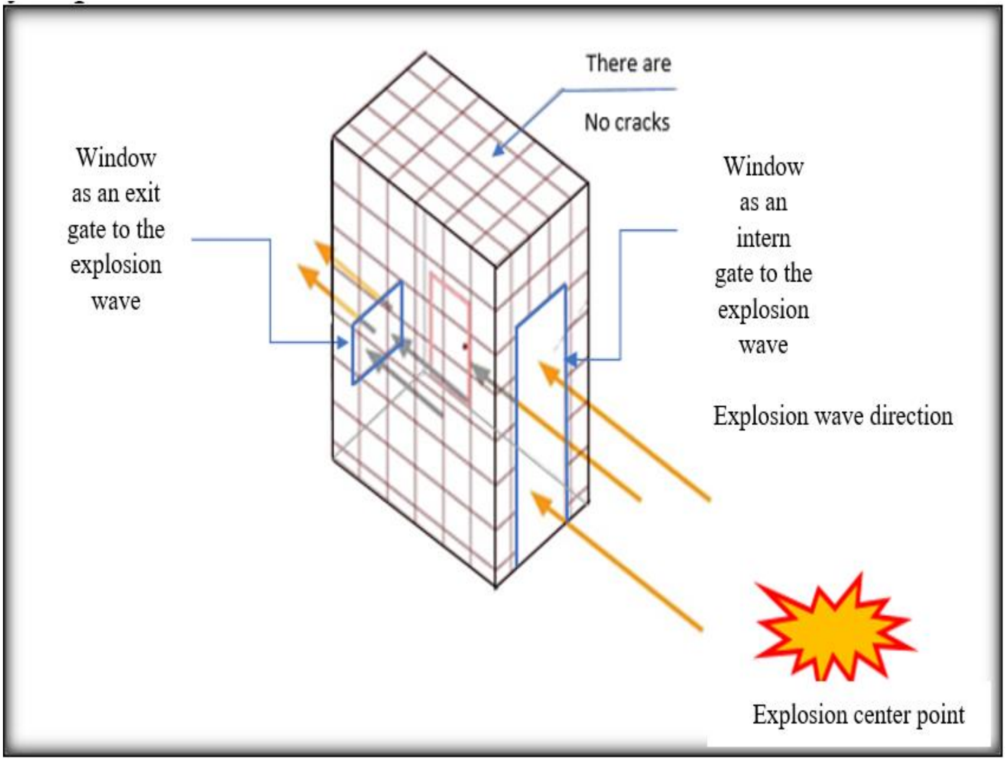

Figure 21: Building has a ventilation hatches (window)

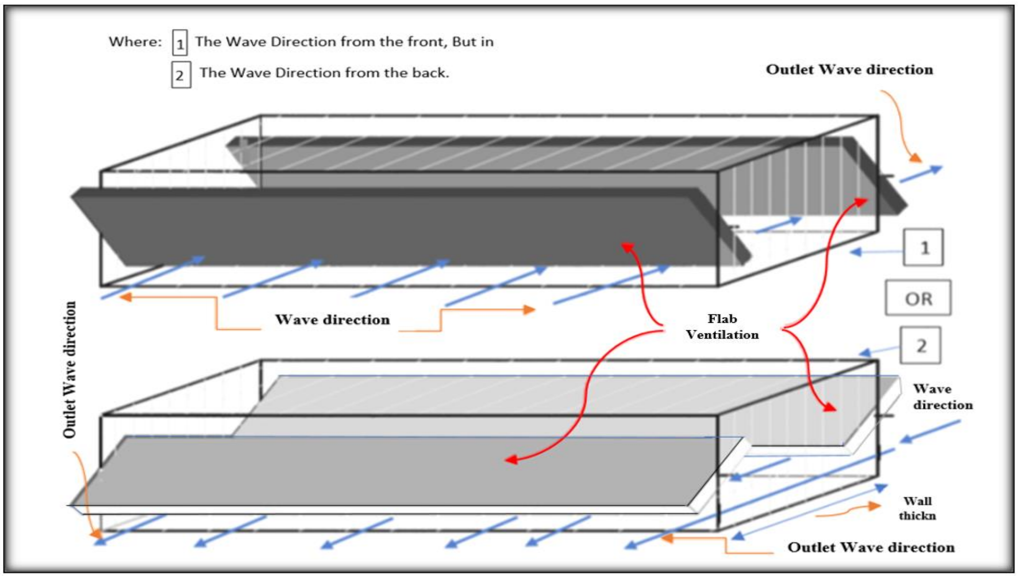

Figure 22: Blast wave Flap Ventilation gate suggested to be in the building design

2. A payload of 250 kg of high explosive (HE) had an observable effect (greaterthan 0) on the Richter magnitude. However, the actual impact resulted from the shock wave generated by the explosion, primarily caused by the scattering of broken concrete parts that were propelled towards surrounding buildings after a direct hit.

Richter Magnitude	Pounds of Explosive	in kg
5	2,000,000,000 pounds	900,909,090 kg
4	200,000,000 pounds	90,909,090 kg
3	20,000,000 pounds	9,909,090 kg
2	2,000,000 pounds	909,090 kg
1	200,000 pounds	90,909 kg
0	20,000 pounds	9,090 kg
-1	2000 pounds	909 kg
-2	200 pounds	90,9 kg
-3	20 pounds	9.1 kg
-4	2 pounds	1 kg

Figure 23: Richter scale[24]

3. Researchers have found that increasing the payload of projectiles does not have a noticeable impact on the Richter magnitude measurement. This implies that the structural damage caused by projectiles is mainly a result of the explosion's shock wave and the subsequent scattering of concrete fragments, which can pose a threat to nearby buildings. Descriptive statistical measures were used; the following indication was found:
The negative value in Table 3 indicates that as the distance from the explosion center increases, the time taken by the shock wave also increases. This means that the force of the shock wave diminishes over time. This relationship is clearly demonstrated by the magnitude, which is less than 0.5 (shown in red) in Table 3.
The research used descriptive statistical measures to analyze the data and found the following relationships:

- There is a negative correlation between the distance from the center of explosion and the time taken, as well as the wave height. This means that as the distance increases, the time taken and wave height decrease.
- There is a direct relationship between time and distance, meaning that as the distance increases, the time taken also increases.
- There is an inverse relationship between time and the magnitude of the shock wave, implying that as the magnitude of the shock wave decreases, the time taken increases.
- The research also found that as the distance between the explosion center and adjacent buildings increases, the arrival time of the shock wave increases, while the strength of the shock wave decreases.
- The significance level of the findings was below 0.05%, indicating a statistically significant result, which is considered a positive sign in the research.

Table 3: Correlations by SPSS Analysis

		Pso	Distance - m	ta - ms/kg
Pearson Correlation	Pso	1.000	-.431	-.488
	Distance - m	-.431	1.000	.962
	ta - ms/kg	-.488	.962	1.000
Sig. (1-tailed)	Pso	.	.012	.005
	Distance - m	.012	.	.000
	ta - ms/kg	.005	.000	.

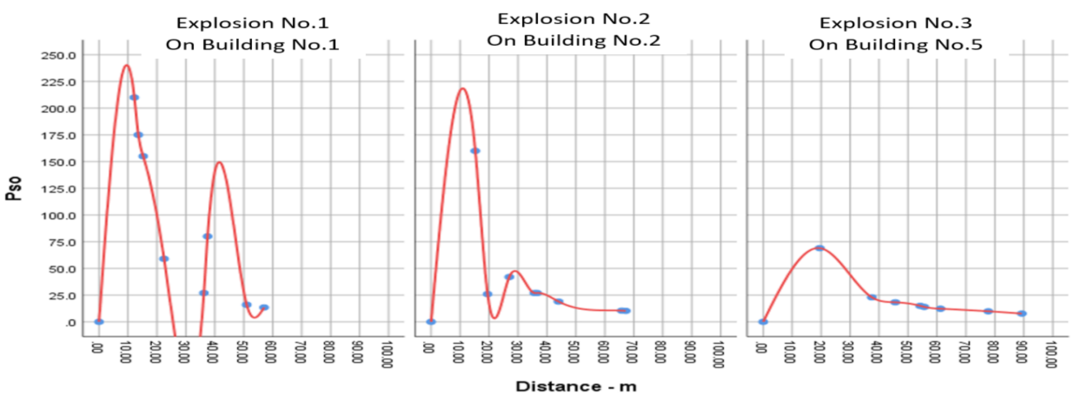

Figure 24: Correlations Charts by SPSS Analysis

Figure 25: Damages in buildings 1 & 2 that directly exposed to bombing

Figure 26: Damages in buildings 1 & 2 that directly exposed to bombing and in buildings 4 & 9 that indirectly exposed to bombing

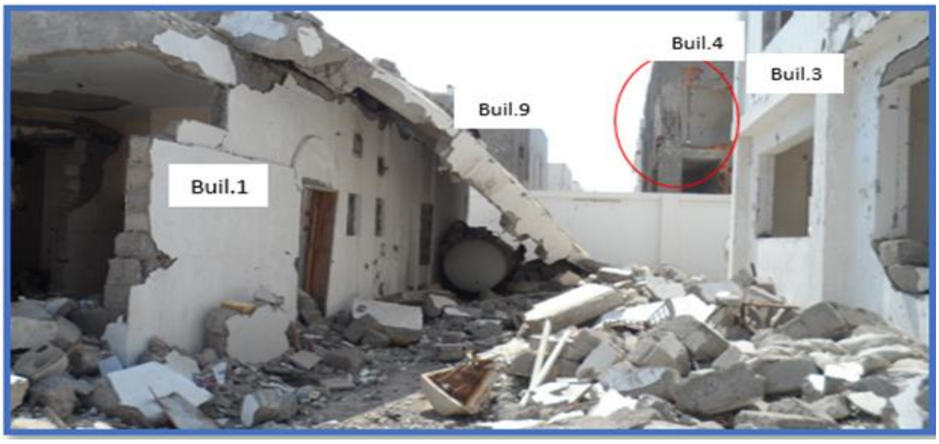

Figure 27: Damages in building 1 that directly exposed to bombing and in buildings 3, 4 & 9 that indirectly exposed to bombing

Figure 28: Buildings 2, 3, 5, and 6

Figure 29: Damages in building 7 & 8 that indirectly exposed to bombing

IX. Conclusions

Based on a case study of a unit of buildings exposed to the indirect effects of an explosion, the study draws the following conclusions:

1. The presence of ventilation hatches in a building reduces the impact of an explosion shock wave compared to a building without any ventilation outlets.
2. Buildings located near an explosion act as protective shields, absorbing the impact and safeguarding the neighboring buildings behind them.
3. The extent of damage to buildings caused by explosion shock waves increases proportionally with the distance from the center of the explosion.
4. Comparing the explosive payload of high explosive ordinance and known projectiles used in conventional war with Richter magnitude measurement is not meaningful or significant.

5. The main cause of damage in an explosion is the shock wave, which is a powerful blast of energy that radiates outward. This shock wave can lead to the fragmentation of concrete structures, causing them to break apart. Additionally, other objects propelled by the explosion can further increase the damage, affecting nearby buildings as well.

Declarations

Availability of data and materials

Not applicable' in this section.

Competing interests

The authors declare that they have no competing interests

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